Using AQM to improve TCP performance over wireless networks

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ABSTRACT

TCP flow control algorithms have been designed for wireline networks where congestion is measured by packet loss due to buffer overflow. However, wireless networks also suffer from significant packet losses due to bit errors and handoffs. TCP responds to all the packet losses by invoking congestion control and avoidance algorithms, which results in degraded end-to-end performance in wireless networks. In this paper, we present a Wireless Random Exponential Marking (WREM) scheme which effectively improves TCP performance over wireless networks by decoupling loss recovery from congestion control. Moreover, WREM is capable of handling the coexistence of both ECN-Capable and Non-ECN-Capable routers. We present simulation results to show its effectiveness and feasibility.

Keywords: TCP, Flow Control, Wireless Networks, AQM

1. INTRODUCTION

Flow control adapts source rates to network congestion. TCP flow control algorithms have been designed for wireline networks where congestion is typically measured and conveyed in terms of packet loss due to buffer overflow. In wireless networks, however, packets are lost mainly due to higher bit errors, channel fading and interference, intermittent connectivity, and handoffs. Traditionally, research has been conducted separately on flow control in wireline networks and on interference suppression in wireless networks. In this paper, we describe a Wireless Random Exponential Marking (WREM) scheme which effectively improves TCP performance over wireless networks by decoupling loss recovery from congestion control. More importantly, WREM is compatible with non-ECN-capable routers, making the scheme highly implementable over both wireline and wireless networks. We present simulation results to show its efficiency and feasibility.

2. PROBLEMS AND RELATED STUDIES

The coupling between packet loss and congestion measure and feedback in Reno leads to poor performance over wireless links. This is because a Reno host cannot differentiate losses due to buffer overflow from that due to wireless effects, and halves its window on each loss event. The unnecessary reduction in the link bandwidth utilization causes poor throughput and very high interactive delays. Several approaches have been proposed to address this problem, but none have worked well [1].

2.1. Impact on TCP by wireless links

In wireless networking, mobile hosts expect the same services offered to fixed hosts in data transport. However, using TCP for the network containing wireless links will lead to severe degrade network throughput. In the following we briefly discuss some important factors.

2.1.1 Limited capacity

The available spectrum is a precious resource in wireless communication. It limits the maximum rate at which packets can be transmitted over the wireless channels. To maintain a reliable service, we have to use forward error coding (FEC) and automatic repeat request (ARQ). However, the error control mechanisms can only partially correct the errors in wireless environments and waist the already limited bandwidth.

2.1.2 High loss probability and error profile

The wireless link has much higher high bit error rate than wireline links. The corrupted packets cause time outs in the TCP sender, resulting in frequent retransmissions, which is always associated with the slow-start phase in TCP. Repeated errors therefore lead to a low throughput. Moreover erroneous packets generate end-to-end retransmissions that create traffic overload in the entire network. In general, the error profile of the wireless link is bursty. In mobile systems, the channel may present a severe fading or conversely good budget link depending on the position of the mobile device.

2.1.3 Higher end-to-end delay

The presence of wireless link on an end-to-end connection will therefore slow down data traffic and increase the end-to-end delay due to its limited capacity. Retransmissions caused by erroneous packets also add a supplementary delay that should be taken into account in calculating the globe delay. Moreover wireless systems often rely on coding and interleaving to cope with high error rate. These methods can increase the wireless delay.

2.1.4 Frequent disconnection

Disconnection means that a temporary bad link quality, resulting in the mobile incapacity to get the information. In cellular wireless communication systems, handoff often leads to variation in packet delays or in packet losses that can cause disconnection lasting from some packets up to a few frames. If a cell contains many users, such as pico-cell, some connections (of newly arriving mobiles) may not receive bandwidth for a long period of time.

2.2. Approaches to improving TCP performance over wireless networks

In order to cope with the problems in wireless networks, some new versions of TCP have been introduced. We broadly classify the schemes for improving the performance of TCP in wireless networks into three categories: (1) end-to-end methods, (2) splitting the connection methods, and (3) link layer methods. The end-to-end methods attempt to make the TCP sender handle losses through the use of two techniques. First, they use some form of selective acknowledgments, such as SACK [2] or fast retransmit [3], to allow the sender to recover from multiple packet losses in a window without resorting to a coarse timeout. The main advantages of these methods are that it reduces the length of disconnection due to handoff and that it can be used to adapt TCP to mobile computing environments without modifying the end-to-end TCP semantic. On the other hand, they require modification to the TCP code at mobile host and do nothing to deal with the error characteristics of the link. Second, they attempt to have the sender distinguish between congestion and other forms of losses using an explicit congestion notification (ECN) mechanism. The splitting the connection methods attempt to separate loss recovery over the wireless link from that across wireline since these two links have totally distinct characteristics. These solutions include Indirect-TCP [4], M-TCP (TCP for mobile cellular networks) [5]. Split methods in general often suffer from high software overhead in case of duplication of protocol stack and require a lot of buffering capacity in the base station. The link-layer methods attempt to hide link-related losses from the TCP sender by using local retransmissions (ARQ) and forward error correction (FEC) over the wireless link. ARQ and FEC succeed in reducing the observed BER from the transport protocol and they naturally fit into the layered architecture of protocol stack. However, all these methods waist the valuable wireless bandwidth. Snoop-TCP [6] is classified as the link layer method and takes advantages of the knowledge of the use of TCP. The Snoop protocol introduces a module, called the snoop-agent, at the base station to avoid unnecessary fast retransmissions and congestion control invocations. But it increases the complexity of process at the base station.

3. WREM

It has been widely recognized that Active Queue Management algorithms (AQM) such as RED [7] and REM [8] are able to improve TCP performance by actively feeding back congestion messages. AQM algorithms use either a packet drop or an ECN [9][10] marker to indicate congestion. When detecting an ECN marker, the Reno host treats it as an indication of packet loss. This property can be exploited to improve the performance of TCP over wireless links by decoupling flow control from loss recovery. We propose a Wireless Random Exponential Marking (WREM) scheme as an optimal approach to TCP over wireless networks.

The key ideas of WREM are:

1. Deploy REM and ECN to decouple flow control from loss recovery while optimizing TCP performance. This improves TCP performance over wireless networks effectively.

2. Set WREM agent at the base station or wireless router to convert packet losses due to buffer overflow to ECN marks. This makes WREM compatible with Non-ECN-Capable routers.

3.1. REM

Recall that to implement RED [7], a router maintains an (exponentially weighted) average queue length as a measure of congestion and marks packets with a probability that is increasing in the congestion measure. Hence, the larger the value of congestion measure, the more severe the congestion, the more likely packets are marked.

REM uses a similar mechanism. It differs from RED in the definition of congestion measure and how it is used to determine the marking probability. In REM, congestion at link l is measured by a quantity called `price' which is updated according to

$$p_l(t+1) = [p_l(t) + \gamma(\ \alpha_l b_l(t) + \hat{x}^l(t) - c_l\ )]^+ \tag{1}$$

where $p_l(t)$ is the price at time t, γ, α_l are positive constants, $b_l(t)$ is the buffer occupancy in period t, $x^l(t)$ is the aggregate input rate at link l, and c_l is the link capacity. In equilibrium, the price stabilizes and the adjustment must be zero. i.e.,

$$\alpha_l b_l(t) + \hat{x}^l(t) - c_l = 0 \tag{2}$$

This can hold if and only if $x^l(t)=c_l$, and the backlog, $b_l(t) = 0$, leading to two key features: match rate and clear buffer, which means it achieves both high utilization and negligible loss and delay.

The marking probability $m_l(t)$ at queue l in period t is exponential to its price $p_l(t)$,

$$m_l(t) = 1 - \phi^{-p_l(t)} \tag{3}$$

where $\phi > 1$ is a constant. The end-to-end marking probability for the packet is then:

$$1 - \prod_{l=1}^{L}(1 - m_l(t)) = 1 - \phi^{-\sum_l p_l(t)} \tag{4}$$

i.e., the end–to–end marking probability is high when the congestion measure of its path, $\sum_l p_l(t)$, is large. When the link marking probabilities $m_l(t)$ are small hence the link prices $p_l(t)$ are small, the end-to-end marking probability given by (4) is approximately proportional to the sum of the link prices in the path,

$$\text{end-to-end marking probability } \approx (\log_e \phi)\sum_l p_l(t) \tag{5}$$

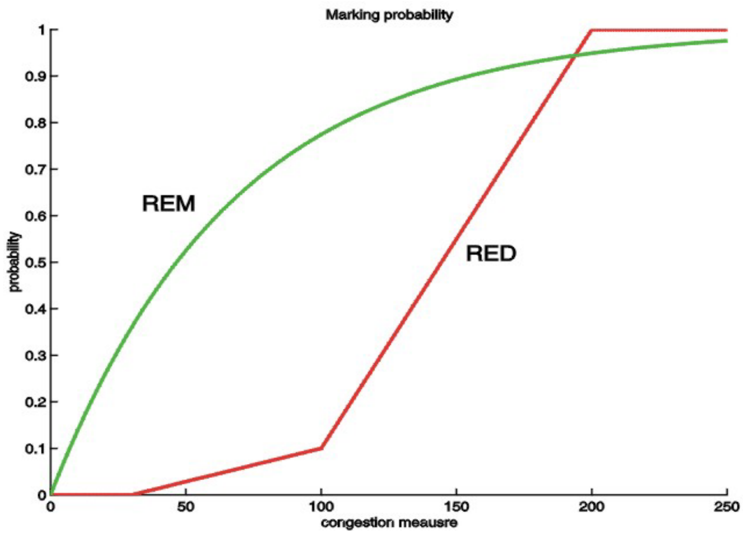


Figure 1: Marking probability of (gentle) RED and REM.

Since REM aims to eliminate packet loss due to buffer overflow, the source sees only wireless losses in equilibrium. We propose to use REM with an ECN marker rather than packet losses to indicate congestion. A TCP source retransmits only when it has detected a loss and halves its window when seeing an ECN marker. This achieves good TCP performance over wireless networks provided that *all* routers through the link are ECN-capable. The advantage of REM over RED is its equilibrium property that has a negligible loss and delay. This provides robustness against burst errors that frequently occur in wireless networks.

However, a major problem with this approach is its application in a heterogeneous network where not all routers are ECN-capable. Routers that are not ECN-Capable continue to assume that losses are due to line congestion. TCP sources that adapt their rates based only on ECN markers run the risk of overloading these routers. In this paper we propose a WREM agent to solve this problem.

3.2. WREM Agent

The ubiquity of the Internet is, at least partly, due to the technology-independent design of IP, which seamlessly interconnects diverse networks. Therefore, accommodating migration is an essential requirement to any new network standards. A good strategy should be able to handle the coexistence of both ECN-Capable and non-ECN-Capable routers.

Packet losses due to buffer overflow may inevitably occur in the Internet. In addition, the non-ECN-Capable routers, even those with AQM algorithm like REM or RED will drop packets when facing heavy congestion. For non-ECN-capable routers, it is the packet loss that indicates line congestion. Thus for networks with such routers, disassociation of packet loss with congestion may lead to failure in congestion control.

To solve this problem, we propose to design a WREM agent as an interface between wireless and wireline networks at the base station or wireless router. In order to decouple loss recovery from congestion control completely, the WREM agent incorporates congestion messages conveyed by packet loss into a unique format: the ECN marker. Before data enters a wireless link, the WREM agent monitors both IP packets going through and ACKs feeding back. Once packet losses due to congestion are detected, an ECN bit is set immediately. This makes it possible to transport all congestion messages to TCP source correctly.

In this scheme, a Reno host uses only ECN messages to invoke congestion control**:** Whenever a packet loss is due to transmission error, the router invokes only the retransmission mechanism and does not reduce its congestion window size. Since packet losses due to transmission errors cannot cause TCP to reduce the window size, WREM can lead to significant performance improvement. Since multiple packets may be marked by WREM within one window, the Reno host reacts to an ECN marker at most once per round-trip time (RTT). This also provides robustness against the possibility of a dropped Wireless-ECN packet in bi-directional paths.

3.3. Major advantages

In comparison, WREM has two major advantages:

1. It improves TCP performance effectively in wireless network and is consistent with the existing TCP mechanism.
2. More importantly, it is compatible with non-ECN-capable routers, making the scheme highly adoptable in both wireline and wireless networks.

4. PERFORMANCE

We have conducted preliminary simulations to compare the performance over wireless networks with and without WREM, with a single link and multiple links containing non-ECN-Capable routers, with various wireless channel models, numbers of sources, link capacities, and propagation delays.

We used the ns-2.1b8 simulator in our simulations with a topology shown in Figure 2 below,

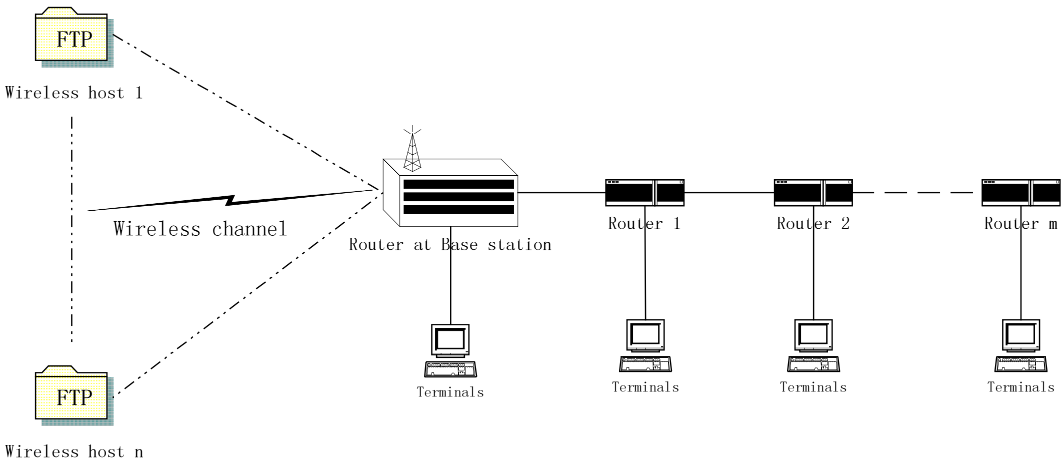


Figure 2: Simulation topology.

The wireless link is shared by N Reno hosts. They all execute File Transfer Protocol (FTP), i.e., all are greedy. FTP sources may go through a single link or multiple links, where routers are randomly set as ECN-capable or non-ECN-capable. We model only one direction of flow of packets from the LAN host to the wireless host, propagation delays are assumed to be negligible. We also assume that ACK's from the wireless terminals arrive instantaneously to the LAN host. Since ACK packets are relatively much smaller than data packets (40-byte ACK's versus 560-1500-byte packets), this is a reasonable assumption. In the following section, we present our test results to validate the effectiveness and the compatibility of WREM.

4.1. Utilization

The ns-2 simulator for a single wireless link has a bandwidth capacity of 2Mbps and a buffer capacity of 120 packets.

We present two sets of results: One uses the Bernoulli error model and the other a Markov chain wireless channel model. Both sets of simulations show that WREM indeed effectively improves the performance of TCP in the wireless network.

4.1.1 The Bernoulli error model

In this simulation, we modeled wireless link simply as a link with a Bernoulli error model. It loses packets with a linear probability. Though this property doesn't match real wireless channels, we present simulation results to show the ability of WREM against lossy links theoretically.

Figure 3 shows the performance when the error probability has varied from 0% to 10%. The wireless link is shared by 32 sources for a duration of 100sec. As expected, the performance steadily decreases as the error probability increases. WREM significantly improves the performance as compared to that of the normal Newreno without WREM. WREM is able to maintain a relatively high utilization while Newreno without WREM has decayed to a poor utilization of around 20% when the error rate is 3%. Even when the error rate reaches 10%, WREM still improves TCP performance from 18% to 49% as shown in Figure 3.

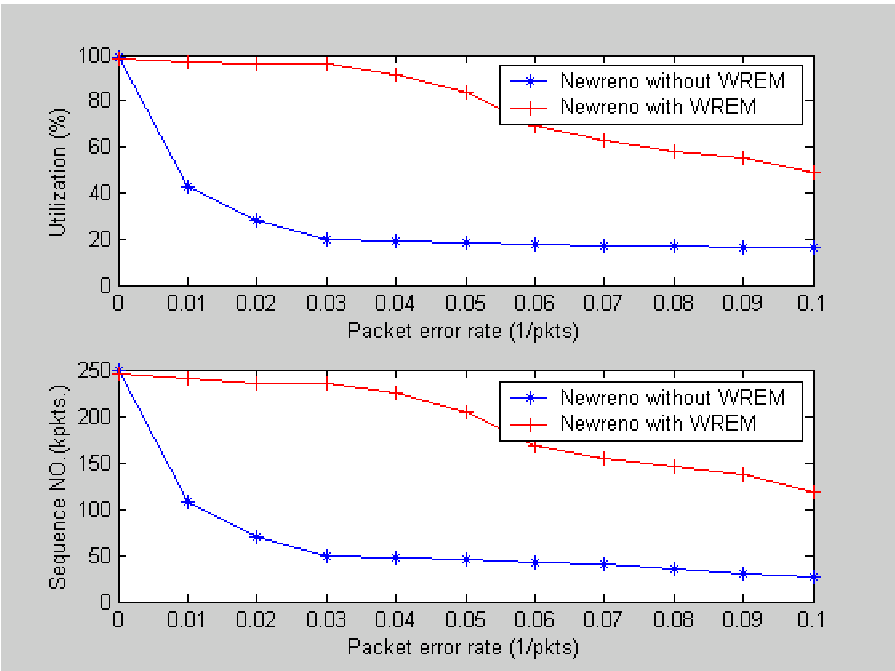


Figure 3: Link utilization and packet sequence number as a function of Bernoulli loss probability.

4.1.2 Markov chain wireless channel model

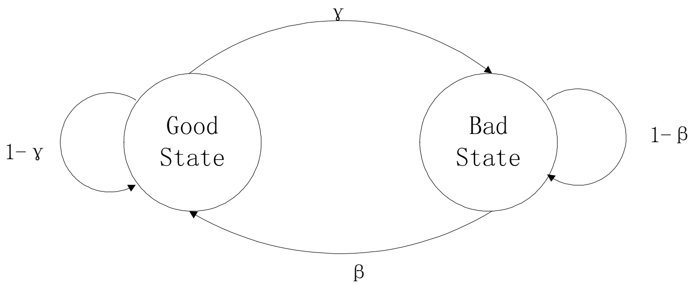
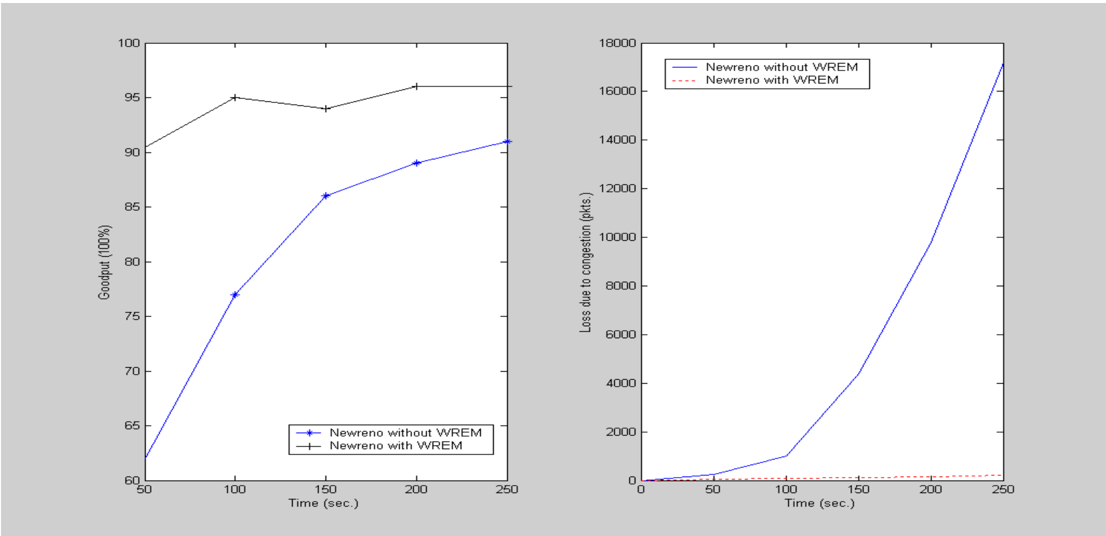


Figure 4: Two States Markov chain wireless channel model.

We have simulated the wireless link by using a two states Markov chain shown in Figure 4. Different channel properties can be obtained by tuning γ and β. This wireless link is shared by 100 NewReno sources (an improved version of Reno). 20 sources are initially active at time 0 and every 50s thereafter, 20 more sources activate until all 100 sources are active. We compare the performance of NewReno with and without WREM.

Figure 5 (a) shows that WREM scheme is very effective in improving the goodput of Newreno, raising it from between 62% and 91% (depending on the number of sources) to between 90.5% and 96%. The cumulative packet losses due to buffer overflow is shown in Figure 5(b). WREM produces negligible losses while Newreno without WREM suffers from steadily increasing packet losses. This is consistent with the instantaneous queue length as shown in Figure 6.



(a) Goodput (%) (b) Cumulative loss (pkts)

Figure 5: Markov chain wireless channel model: Performance comparison.

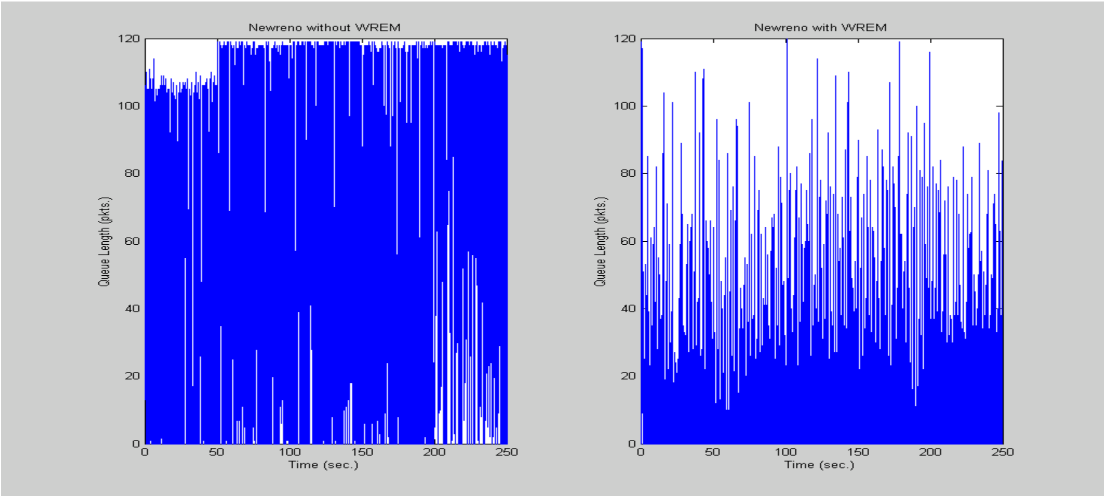


Figure 6:Markov chain wireless channel model: Instantaneous queue length.

4.2. Compatibility

We execute this simulation with multiple links that consist of both non-ECN-capable and ECN-capable routers. To simplify, we put only two routers into the path: One is running REM and the other is non-ECN-capable. We used the two-states Markov chain to simulate the wireless link. In this simulation, we used 100 Newreno sources which were activated sequentially every 50 seconds. We compare the performance with the result under the same topology but both routers are running REM to validate its compatibility.

Figure 7 shows that upon the presence of non-ECN-capable routers, WREM achieves almost the same performance as when all routers are ECN aware, i.e., WREM is compatible with both ECN-capable and non-ECN-capable routers.

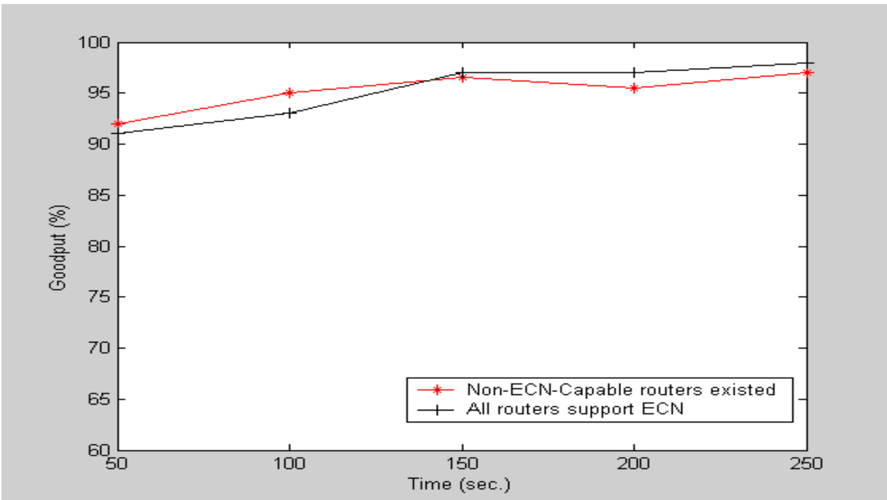


Figure 7: Compatibility: Performance comparison when both ECN-capable and non-ECN-capable routers exist.

Although networks with non-ECN-capable routers can maintain a high utilization by using WREM, we still recommend that all routers adopt AQM algorithm such as REM. Figure 8 shows that REM is able to stabilize the average queue at a low level thus lead to low queuing delay and loss rate.

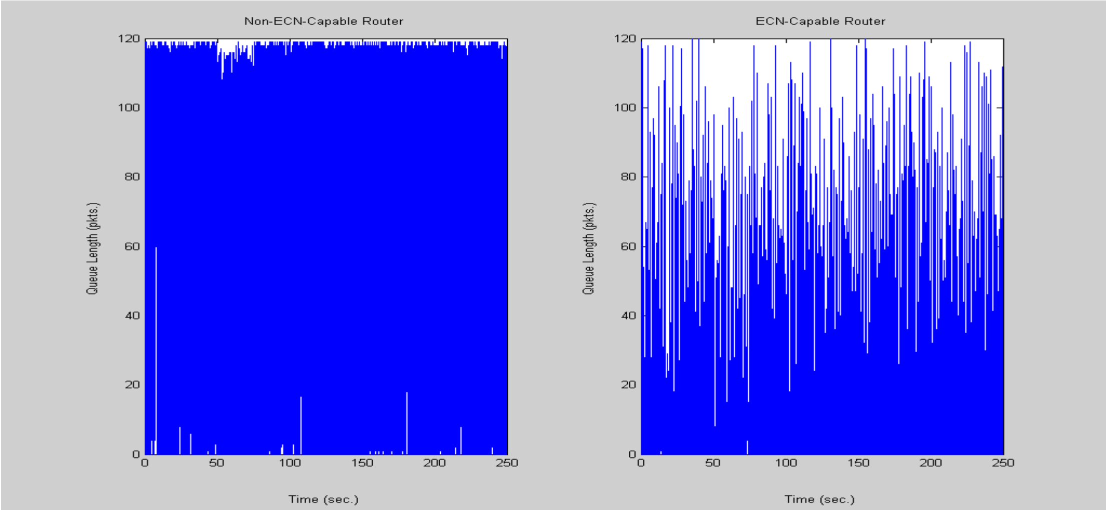


Figure 8: Instantaneous queue length at non-ECN-capable router and REM.

5. CONCLUSION

Active queue management algorithms have been widely recognized as an effective way to improve TCP performance. In this paper we have proposed the WREM scheme which separates packet losses due to transmission error from that due to congestion. Our WREM scheme has shown its effectiveness in improving TCP performance of the Internet that has wireless components with both ECN-capable and non-ECN-capable routers. WREM has the desired ability to improve TCP performance in wireless network and maintain the Internet TCP protocol integrity. Our simulations have shown that WREM is compatible with non-ECN-capable routers, making it highly adoptable in both wireline and wireless networks. Currently we are investigating the effects of vertical integration of WREM in the TCP/IP protocol suite, the network capacity implication of WREM, and its dynamic properties in large internetworked environments.

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